A Rich Population of X-ray Emitting Wolf-Rayet Stars in the Galactic Starburst Cluster Westerlund 1

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ABSTRACT

Recent optical and infrared studies have revealed that the heavily-reddened starburst cluster Westerlund 1 (Wd 1) contains at least 22 Wolf-Rayet (WR) stars, comprising the richest WR population of any galactic cluster. We present results of a sensitive *Chandra* X-ray observation of Wd 1 which detected 12 of the 22 known WR stars and the mysterious emission-line star W9. The fraction of detected WN stars is nearly identical to that of WC stars. The WN stars WR-A and WR-B as well as W9 are exceptionally luminous in X-rays and have similar hard heavily-absorbed X-ray spectra with strong Si XIII and S XV emission lines. The luminous high-temperature X-ray emission of these three stars is characteristic of colliding wind binary systems but their binary status remains to be determined. Spectral fits of the X-ray bright sources WR-A and W9 with isothermal plane-parallel shock models require high absorption column densities $\log N_{\rm H} = 22.56$ (cm^{-2}) and yield characteristic shock temperatures $kT_s \approx 3$ keV ($T_s \approx 35$ MK).

Subject headings: open clusters and associations: individual (Westerlund 1) — stars: formation — stars: Wolf-Rayet — X-rays: stars

1.   Introduction

The heavily-reddened cluster Westerlund 1 (Wd 1; Westerlund 1961, 1987) in Ara has recently been recognized as a rare example of a starburst cluster in our own Galaxy. The cluster is massive, compact, and young with age estimates of $\sim$3 - 5 Myr (Brandner et al. 2005 = B05; Clark et al. 2005 = C05). Wd 1 contains a remarkable collection of massive post-main sequence stars including early and late-type supergiants, a luminous blue variable candidate, and the largest known population of Wolf-Rayet (WR) stars of any galactic cluster (C05; Negueruela & Clark 2005 = NC05; Clark & Negueruela 2002). A recent *VLT* study has also revealed a faint population of low-mass pre-main sequence stars and gives a photometric distance d = 4.0 $\pm$ 0.3 kpc (B05), but spectroscopic studies allow a larger range of distances (C05). The extinction is $A_V \approx$ 9.5 - 13.6 mag (B05, C05).

Ongoing studies have so far identified 22 WR stars in Wd 1 and the census is likely incomplete. WR stars are highly-evolved evolutionary descendants of massive O-type stars that are in advanced nuclear burning stages and undergoing extreme mass-loss from high-velocity winds, rapidly approaching the end of their lives as supernovae. At least one supernova has already occurred in Wd 1 as evidenced by the discovery of a new X-ray pulsar (Figure 1; Skinner et al. 2005a = S05a; Muno et al. 2006).

There is at present no comprehensive theory of X-ray emission from WR stars. Previous observations have focused mainly on X-ray bright WR + OB binaries such as γ^2 Vel and WR 140 (Skinner et al. 2001; Zhekov & Skinner 2000), whose hard emission (kT $\geq$ 2 keV) is thought to originate primarily in colliding wind shocks. Much less is known about the X-ray emission of single WR stars, but by analogy with O-type stars they are expected to emit soft X-rays (kT < 1 keV) from instability-driven shocks formed in their supersonic winds (Gayley & Owocki 1995). Despite these expectations, X-ray emission from single WR stars has proven difficult to detect. Recent sensitive observations have shown that single carbon-rich WC stars are exceedingly faint in X-rays or perhaps even X-ray quiet,for reasons that are not yet fully understood (Skinner et al. 2005b = S05b). Additional X-ray observations are needed to quantify X-ray emission properties across the full range of WC and WN spectral subtypes.

The presence of a rich, equidistant, coeval population of WR stars in Wd 1 makes it an opportune target for X-ray observations, which are capable of penetrating the high extinction. We present the results of a sensitive *Chandra* X-ray observation of Wd 1, focusing here on the WR population. This observation yields 12 new WR X-ray detections and provides valuable new information on the X-ray properties of this unique sample of galactic WR stars that can be used to test shock emission models and guide new theoretical development.

2. Chandra Observations

Chandra observed Wd 1 on 22-23 May 2005 and 18-19 June 2005 with exposure live times of 18,808 s and 38,473 s respectively. The observations were obtained with the ACIS-S imaging array in timed faint event mode using a 3.2 s frame time. The pointing positions were (J2000.0): R.A. = 16^h 47^m 08.60^s, $-45°$ $50'$ $27.4''$ in May 2005 and R.A. = 16^h 47^m 07.78^s, $-45°$ $51'$ $00.9''$ in June 2005.

Data reduction was based on Level 2 event files generated by the *Chandra* X-ray Center. Source detection was accomplished using the CIAO [1] (vers. 3.2.1) tool *wavdetect* applied to full resolution images ($0.''492$ pixel size) that were energy filtered to include only events in the [0.3 - 7] keV energy range to reduce background. The 3σ elliptical source regions generated by *wavdetect* were used to extract an event list for each source. The source event lists were used for further timing and spectral analysis. The probability of constant count rate P_c was computed for each source using the non-parametric K-S statistic (Skinner, Gagné, & Belzer 2003 and references therein). Spectra and associated instrument response files for brighter sources were extracted from updated Level 2 event files using recent CIAO vers. 3.3 tools that incorporate the latest gain and effective area calibrations (CALDB vers. 3.2). Spectra were analyzed using XSPEC vers. 12.2.0.

3. Wolf-Rayet Stars

3.1. Wolf-Rayet Star X-ray Detections

Chandra detected 12 of the 22 known WR stars in Wd 1, including 11 of the 19 WR stars in the list of NC05 and 1 of the 3 WR stars (all of WN subtype) identified by Groh et al. (2006). Their positions are shown in Figure 1 and X-ray properties are summarized in Table 1. The detection rate was similar for WN and WC stars. Specifically, 8 of 15 (53%) of the known WN stars were detected and 4 of 7 (57%) WC stars. However, the WC9 star WR-E is considered to be a marginal detection.

Three WR detections show signs of variability, but two of these are faint sources with few counts on which to base a variability analysis. Both WR-K (source 2) and WR-G (source 3) were faintly detected in the first observation but not in the deeper second observation. WR-G had a low probability of constant count rate $P_c = 0.003$ in the first observation and

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[1]Further information on *Chandra* Interactive Analysis of Observations (CIAO) software can be found at http://asc.harvard.edu/ciao.

a noticeably high mean photon energy. WR-B (source 7) is a suspected WN8 + OB binary (NC05) and had $P_c = 0.15$ in the second observation. A low-amplitude rise and fall can be seen in its X-ray light curve but no variability was seen in WR-B during the first observation.

Table 1 gives the X-ray luminosities of WR stars in Wd 1 and the L_x distribution is shown in Figure 2. The median X-ray luminosity of the detected WN stars log $L_x = 32.23$ (ergs s^{-1}) is only slightly larger than the median log $L_x = 32.02$ for WC stars. The stars WR-A (source 13) and WR-B (source 7), both of which have uncertain WN spectral types (C05), have very high L_x and are very likely binaries. At the other extreme, 45% of the WR stars in Wd 1 were undetected and the shape of the L_x distribution at low luminosities is not well-determined.

3.2. Wolf-Rayet Star Non-detections

Chandra did not detect 10 of the 22 known WR stars in Wd 1 down to the detection limit log L_x (0.3 - 7 keV) ≈ 31.3 ergs s^{-1}, which assumes a 6 count threshold in 57.3 ksec and underlying thermal spectrum with kT = 1 keV and $N_H = 3 \times 10^{22}$ cm^{-2}. Higher X-ray absorption in the metal-rich winds of WC stars would decrease the chance of their X-ray detection but does not explain why the fraction of undetected WN stars is just as high as WC stars. If the non-detections are predominantly single stars that emit only softer X-rays at kT < 1 keV, as occurs for many O-type stars, their emission would be preferentially absorbed and they could escape detection.

Although N_H and X-ray temperature clearly affect X-ray detectability, convincing evidence is now emerging for very large differences in L_x in WR stars with similar spectral types. In the Wd 1 sample, the WC9 star WR-F (source 6) was clearly detected as a moderately bright X-ray source (log $L_x = 32.60$ ergs s^{-1}) but the WC9 stars WR-M and WR-H were undetected with count rate limits that are at least ten times smaller. Furthermore, we note that a previous 20 ksec *Chandra* observation failed to detect the single WC8 star WR 135 in Cygnus with a conservative upper limit log L_x (0.5 - 7 keV) ≤ 29.82 ergs s^{-1}, which gives a remarkably low ratio log $[L_x/L_{bol}] \leq -9.1$ (S05b). Assuming d = 1.74 kpc and low extinction $A_V = 1.26$ mag (van der Hucht 2001), it is difficult to attribute the WR 135 non-detection entirely to absorption. Despite their similar WC8-9 spectral types, WR-F and WR 135 differ in L_x by at least a factor of ≈ 600. There are no indications for binarity in WR 135 and other attempts to detect apparently single WC stars have yielded negative results (S05b). Thus, single WC stars emit X-rays at very low levels (if at all) and the elevated X-ray emission of WC stars such as WR-F in Wd 1 is very likely the result of extraneous factors such as binarity.

3.3. Wolf-Rayet Star X-ray Spectra

The *Chandra* spectra of the brightest WR detections reveal similar properties. They are heavily absorbed below $\approx$1 keV and have significant emission above kT $\simeq$ 2 keV. The spectrum of the brightest WR detection WR-A (Fig. 3) shows low-energy absorption as well as strong Si XIII (1.86 keV) and S XV (2.46 keV) emission lines. These lines emit maximum power at log T_{max} = 7.0 (K) and 7.2 (K) respectively. The spectrum of WR-B is similar and shows prominent Si XIII and S XV lines, as does W9 (Fig. 3).

The presence of hotter plasma is not anticipated from models of radiative shocks distributed in the winds of single stars. The harder spectra detected here are clearly of a different origin, and colliding wind shocks in binary systems are a plausible explanation. To investigate this, we have fitted the spectrum of WR-A with the plane-parallel 1T shock model *vpshock* (Borkowski, Lyerly, and Reynolds 2001) in XSPEC vers. 12.2 using the most recent APED atomic data base (neivers 2.0 in XSPEC).

The *vpshock* model gives very good fits for WR-A with shock temperatures kT_s = 3.5 [2.5 - 4.8; 90% conf.] keV, N_H = 3.6 [3.1 - 4.2] $\times$ 10^{22} cm^{-2}, and reduced χ^2 = 1.0 - 1.1. The above N_H equates to A_V = 16.2 [14.0 - 18.9] mag or E(B-V) = 5.45 [4.70 - 6.36] using Gorenstein (1975). Two-temperature optically thin thermal plasma models give similar N_H values. By comparison, previous studies of the OB supergiants in Wd 1 yield median values A_V = 13.6 mag or E(B-V) $\approx$ 4.35 (C05). This suggests that the extinction across Wd 1 is quite inhomogeneous or excess absorbing material such as cold gas is present toward WR-A that has escaped optical detection. The *vpshock* fits give an upper limit on the ionization timescale log $\tau \leq$ 11.2 (s cm^{-3}), where τ = $n_e t_s$, n_e is the postshock electron density, and t_s is the shock age. Such a low value of τ implies that non-equilibrium ionization effects in the shocked plasma may be important.

4. The Unusual Emission Line Star W9

The enigmatic emission line star W9 lacks any recognizable photospheric features in its R-band spectrum and shows a very broad Hα line (C05). It was classified as a B[e] supergiant by C05 but its nature is uncertain and they note that it could contain a WR component so we discuss it here. *Chandra* detected a strong X-ray source (source 4 in Table 1) at an offset of 0.″3 from the position of W9 given in C05. Two radio sources lying $\approx$15″ to the east of W9 identified as Ara A (N) and Ara A (S) by Clark et al. (1998) were located near the *Chandra* aimpoint but not detected.

The X-ray properties of W9 are very similar to the X-ray bright WN star WR-A. They

have nearly identical mean photon energies (Table 1), L_x (Fig. 2), and spectra (Fig. 3). There is little doubt that their X-ray emission is due to the same process and we suspect that both W9 and WR-A are colliding wind binaries. Spectral fits of W9 with the *vpshock* model give values for N_H, kT_s, and τ that are within 30% of those quoted above for WR-A and the best-fit W9 column density is $N_H = 3.6$ [2.6 - 4.9; 90% conf.] $\times 10^{22}$, or $A_V = 16.4$ [11.8 - 22.3] mag. cm^{-2}. Thus, as for WR-A, the X-ray absorption may exceed that expected from previous A_V estimates.

5. Conclusions

There are good reasons to believe that most of the WR X-ray detections in Wd 1 are binaries. This conclusion is more secure for WC stars than WN stars since there have been no previous X-ray detections of single WC stars, even at better sensitivities than obtained here. Large differences in L_x between WR stars of similar spectral type can be naturally explained if the luminous X-ray sources are colliding wind binaries. Furthermore, *Chandra* preferentially detects harder X-ray sources in Wd 1 because of the high extinction. Plane-parallel shock models give good fits of the brightest X-ray detections and require shock temperatures $kT \geq 2$ keV. Such temperatures are higher than predicted for radiative shocks distributed in the winds of single stars, but are consistent with colliding wind emission in binary systems. Even so, more definitive proof of binarity is needed from optical/IR follow-up work. And, interesting questions remain in the X-ray regime. What is the origin of the excess absorption that is inferred from X-ray spectral fits of WR-A and W9? How does the WR X-ray luminosity function behave at low L_x: are the undetected WR stars faint sources below our detection limit or are they X-ray quiet?

Table 1. Wolf-Rayet Star X-ray Sources in Westerlund 1[a]

No.	R.A. (J2000)	Decl. (J2000)	Counts (c)	Rate (c s^{-1})	<E> (keV)	P_c	log L_x (ergs/s)	Identification	WR Id.
1[c]	16 46 59.91	-45 55 25.6	11 ± 4	5.85E-04	2.84	0.46	32.06	2M 164659.90-455525	N (WC)
2[c]	16 47 03.04	-45 50 43.4	9 ± 3[b]	4.82E-04	2.22	0.57	31.98	2M 164703.15-455043	K (WC)
3[c]	16 47 04.06	-45 51 25.1	13 ± 4	6.93E-04	3.99	0.003	32.14	NT 164704.00-455125	G (WN)
4[d]	16 47 04.14	-45 50 31.4	334 ± 19	8.68E-03	2.63	0.63	33.77[g]	2M 164704.15-455031	W9[e]
5[d]	16 47 04.19	-45 51 07.2	67 ± 9	1.74E-03	2.82	0.85	32.54	NT 164704.23-455107	L (WN)
6	16 47 05.21	-45 52 25.1	77 ± 9	2.01E-03	3.16	0.49	32.60	NT 164705.23-455225	F (WC)
7[d]	16 47 05.37	-45 51 04.9	185 ± 14	4.81E-03	2.49	0.15[h]	33.57[g]	NT 164705.35-455104	B (WN)
8	16 47 05.99	-45 52 08.3	6 ± 3[b]	1.56E-04	1.90	0.61	31.49	GS 164705.99-455208	E (WC)
9	16 47 06.01	-45 50 23.1	27 ± 6	7.01E-04	2.96	0.82	32.14	2M 164706.01-455023	R (WN)
10	16 47 06.26	-45 51 26.8	16 ± 5	4.05E-04	5.02	0.49	31.90	NT 164706.30-455126	D (WN)
11	16 47 07.62	-45 49 22.3	17 ± 4	4.29E-04	3.92	0.70	31.93	2M 164707.61-454922	3 (WN)[f]
12	16 47 07.65	-45 52 36.0	40 ± 7	1.03E-03	2.30	0.43	32.31	2M 164707.64-455235	O (WN)
13[d]	16 47 08.35	-45 50 45.5	500 ± 23	1.30E-02	2.68	0.92	33.92[g]	NT 164708.34-455045	A (WN)

[a]Notes: Data are from the 38,473 s exposure on 18-19 June 2005 unless otherwise noted. All quantities are computed using events in the 0.3 - 7.0 keV energy range. *Chandra* positions are from full-resolution (0.″492 pixel) ACIS-S images. X-ray counts inside *wavdetect* 3σ source detection regions are background-subtracted. <E> is the mean photon energy and P_c is the probability that the count rate was constant based on the K-S statistic. Unabsorbed X-ray luminosities L_x (0.3 - 7 keV) are from PIMMS simulations using a 1T Raymond-Smith thermal plasma model with kT = 1 keV, N_H = 3 x 10^{22} cm^{-2}, and d = 4 kpc unless otherwise noted, and have typical uncertainties ±0.4 dex. Candidate identifications lie within 1″ of the X-ray position and are from the *Hubble Space Telescope* Guide Star Catalog (GS) v2.2, the 2MASS (2M) data base, and archival *New Technology Telescope* (NT) images (J,H,K$_s$ bands). WR star identifications are from Table 2 of Negueruela & Clark (2005) unless otherwise noted. Exposure live times are obs1 (22-23 May 2005): 18,808 s, obs2 (18-19 June 2005): 38,473 s.

[b]Faint source, classified as a possible detection.

[c]Tabulated data are from events collected in the first 18.8 ksec observation.

[d]Source was detected in both observations. Tabulated data are from events collected in the second 38.5 ksec observation.

[e]W9 is listed as source 9 in Table 1 of Clark et al. (2005) who classify it as sgB[e].

[f]Source 3 in Groh et al. (2006).

[g] L_x is from spectral fit.

[h] Low level variability may be present in source 7 (WR-B) during the second observation, but a K-S test gives P_c = 0.86 for the first observation. The mean count rates in both observations were the same to within the uncertainties.

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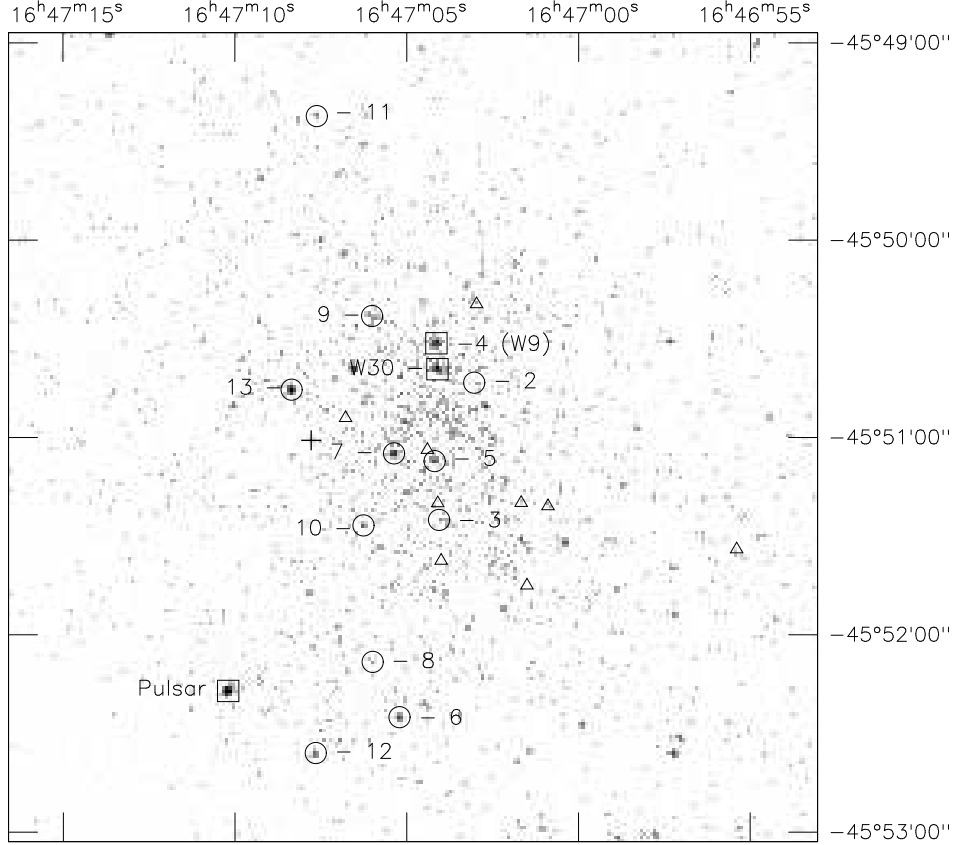
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Fig. 1.— Chandra ACIS-S image (0.3 - 7 keV) of the central region of Wd 1 obtained on 18-19 June 2005 (38.5 ksec). The image has a logarithmic stretch and is rebinned by a factor of two to a pixel size of 0.984″. A plus sign (+) marks the *Chandra* aimpoint. Circles enclose X-ray detected WR stars (Table 1). Source 1 (WR-N) lies to the south and is not shown. Triangles mark positions of undetected WR stars. Squares enclose the bright X-ray sources W9 (B[e]sg), W30 (OB), and a newly-discovered X-ray pulsar. Coordinates are J2000.
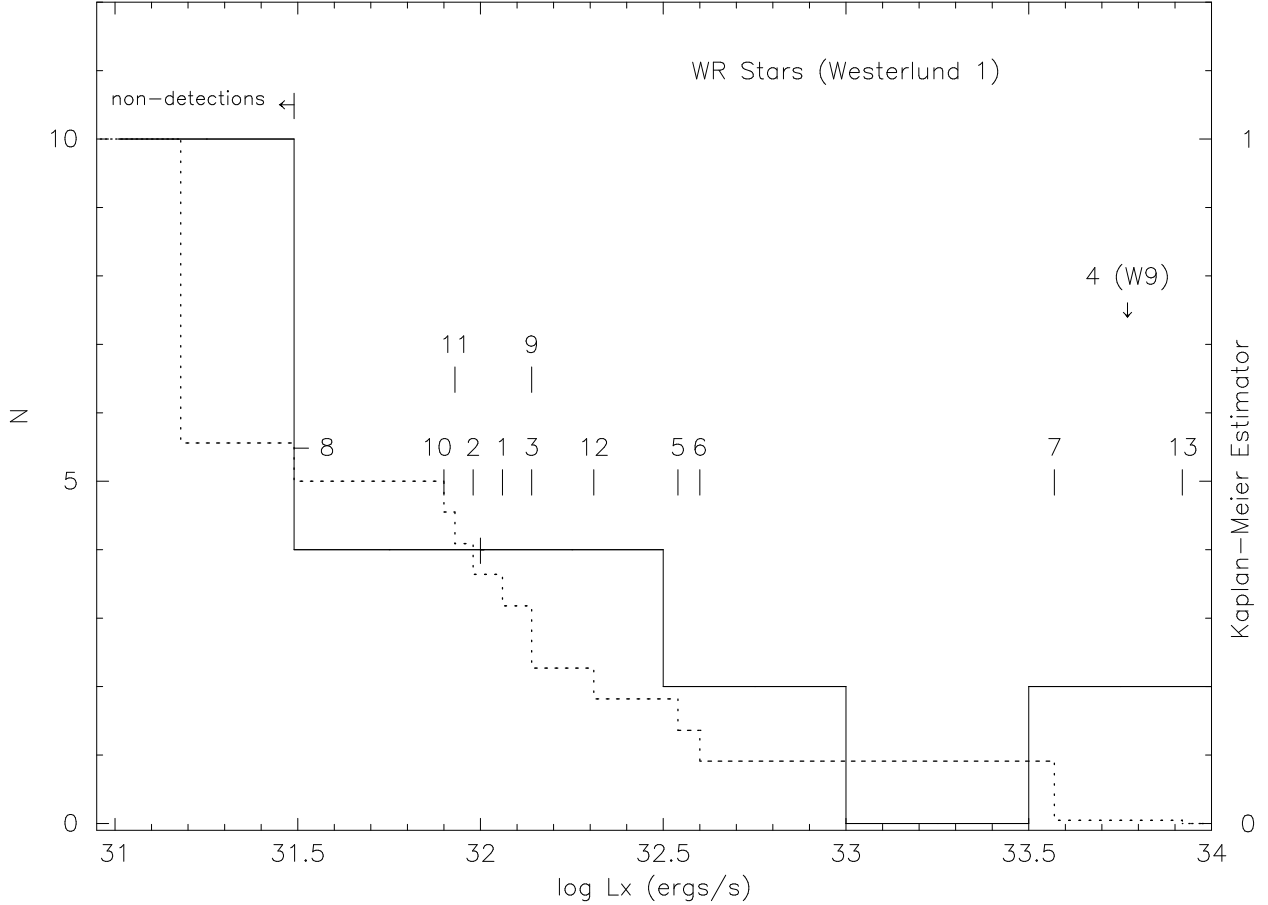
Fig. 2.— Number of WR stars (N) versus unabsorbed X-ray luminosity L_x (0.3 - 7 keV) in Wd 1, assuming d = 4 kpc (B05). Source numbers correspond to Table 1. W9 is also shown for comparison. For brighter detections (4, 7, 13), L_x was determined from spectral fits (Secs. 3.3, 4.0). For fainter detections and non-detections, L_x was estimated from the observed count rate (or upper limit) and the PIMMS simulator (http://asc.harvard.edu/toolkit/pimms.jsp) assuming a 1T thermal plasma model with kT = 1 keV and $N_H = 3 \times 10^{22}$ cm^{-2}. The dotted line shows the Kaplan-Meier estimator for all 22 WR stars, taking upper limits into account.
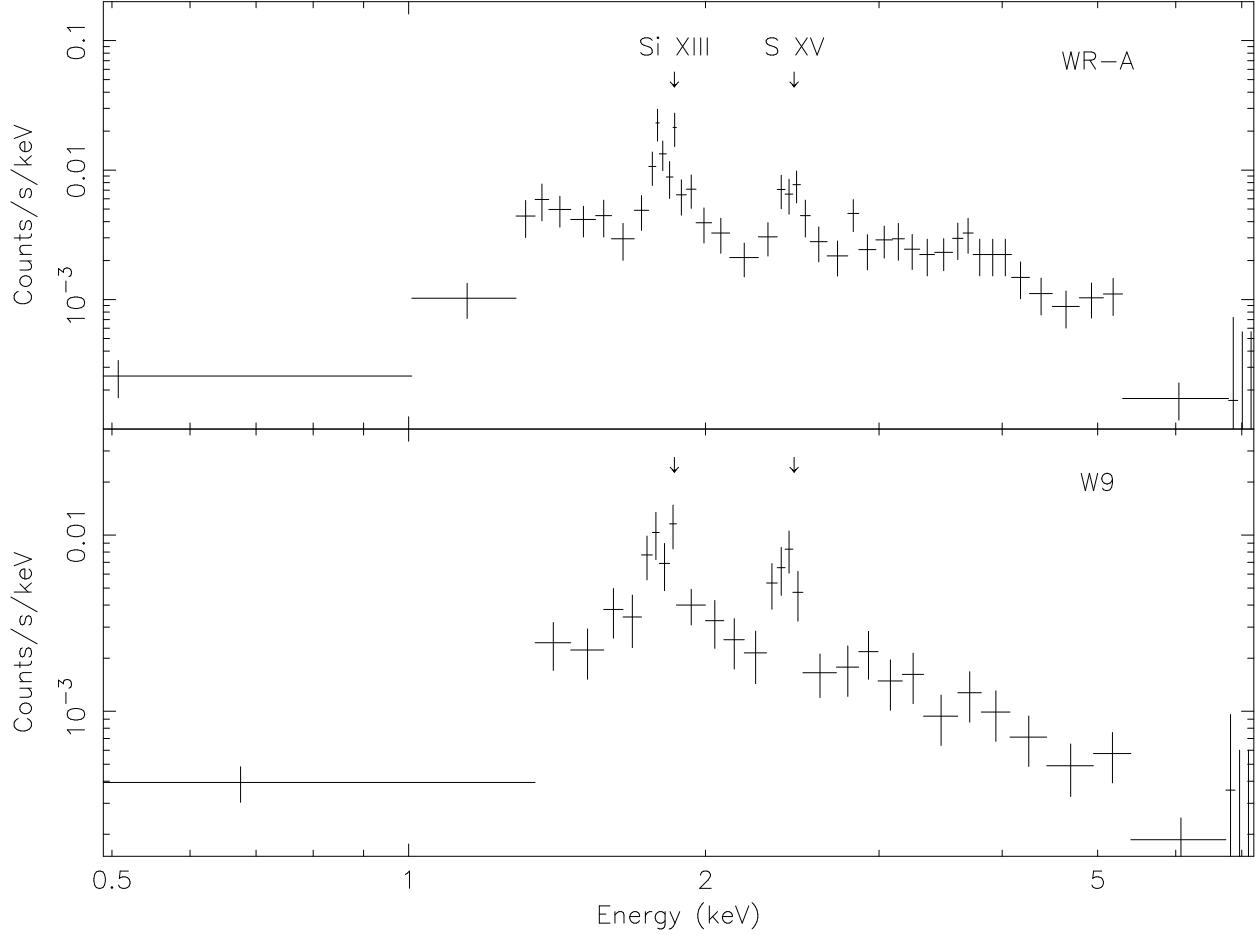
Fig. 3.— Background subtracted *Chandra* ACIS-S spectra of the WN star WR-A and the emission-line star W9. Spectra are from the 38.5 ksec observation on 18-19 June 2005 and are binned to a minimum of 10 counts per bin.